

Impact of Spacecraft Shielding on Direct Ionization Soft Error Rates

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Abstract— We use ray tracing software to model various levels of spacecraft shielding complexity and energy deposition pulse height analysis to study how it affects the direct ionization soft error rate of microelectronic components in space. The analysis incorporates the galactic cosmic ray background, trapped proton, and solar heavy ion environments as well as the October 1989 and July 2000 solar particle events.

Index Terms—soft error rate, direct ionization, radiation transport, space environment.

I. INTRODUCTION

SOLAR activity controls space weather and affects the Earth's atmosphere, including a plasma-physical process called magnetic reconnection, which is the fast release of magnetic energy when oppositely-pointing magnetic field lines are torn apart and reattached to their neighbors. However, we do not understand in depth the physical details of this process. NASA's Magnetospheric MultiScale (MMS) mission [1] is being launched to study magnetic reconnection in Earth's own magnetic field and thereby gain a better understanding of the process in general and specifically how it applies to the production of larger magnetohydrodynamic events like solar flares [2].

To maximize chances of observing reconnection events in Earth's magnetosphere, MMS is being launched during the solar maximum period. Solar maximum, while increasing the probability of gathering good science data, increases the cumulative mission fluence of solar particles incident on the spacecraft, driving up total ionizing dose (TID) as well as rates for soft errors and other single-event effects (SEE) [3-5]. Increased TID and SEE rates occur in addition to the ever-

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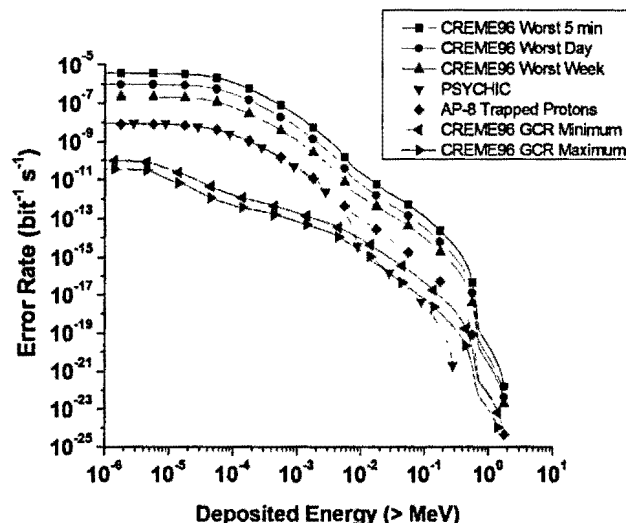


Fig. 1: SiO₂ SV1 soft error rate relationships for several different space environments behind 2.5 mm of solid aluminum spherical shielding. All environments are derived from CRÈME96 with the exception of trapped protons and PSYCHIC. The deposited energy becomes the critical energy once a bin is chosen and the rate evaluated. The symbols are sparse to aid viewing – there are 240 bins per trace. The rate curve family for the silicon SV1 is similar. Note that the PSYCHIC and trapped proton environments are cumulative fluences that were scaled by the inverse of the integration period to convert them to average rates.

present background flux of galactic cosmic rays (GCR) [6], which are also modulated by solar activity.

Although ray trace techniques are commonly used to evaluate complex shielding geometries and obtain TID requirements for space missions, SEE requirements are often determined from simple assumptions about shielding. For example, the Cosmic Ray Effects on Microelectronics code (CRÈME) suite of programs only allows a user the option of doing calculations in solid aluminum sphere geometry with energy deposition based on silicon [7-9]. Due to the increasing sensitivity and complexity – both operational and physical construction – of some devices to SEE, this no longer appears to be adequate. Recent laboratory results show that protons having energies in the vicinity of the Bragg peak can cause soft errors [10-12]. This is a serious concern for space missions because protons are the most abundant element in the space environment. A quantitative analysis of the SEE performance of such devices in space requires accurate models of the shielding geometry and materials provided by the spacecraft in order to track proton energies down to their end of range and determine if soft errors occur.

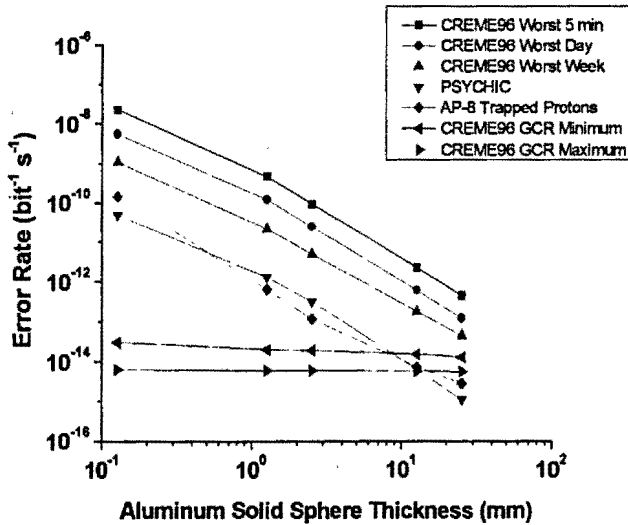


Fig. 2(a): SiO₂ SV1 soft error rates for most of the environments in this study with various solid aluminum sphere thicknesses as shielding. The worst 5 min, worst day, worst week, solar minimum, and solar maximum environments are from CREME96. The PSYCHIC environment was calculated at the 95% confidence level. Note that the PSYCHIC and trapped proton environments are cumulative fluences that were scaled by the inverse of the integration period to convert them to average rates.

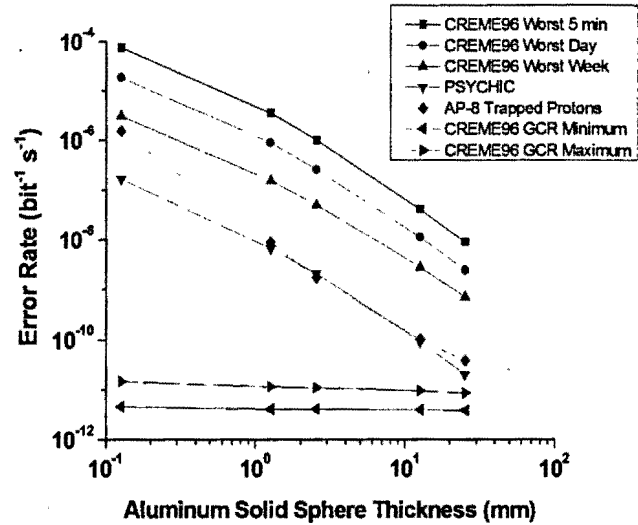


Fig. 2(b): Silicon SV2 soft error rates for most of the environments in this study with various solid aluminum sphere thicknesses as shielding. The worst 5 min, worst day, worst week, solar minimum, and solar maximum environments are from CREME96. The PSYCHIC environment was calculated at the 95% confidence level. Note that the PSYCHIC and trapped proton environments are cumulative fluences that were scaled by the inverse of the integration period to convert them to average rates.

While the assumption that SEE rates due to GCR are fairly insensitive to shielding can be justified [7], solar particle events are much more sensitive to shielding. Since the energy spectra of solar event particles is generally softer than those of GCR, use of actual spacecraft shielding in such an analysis can make a significant difference. Recently, a new model of solar particle event energy spectra has been developed [5], which now allows us the opportunity to do this and compare to standard results such as the worst week, worst day, and peak 5-minute environments in tools like the CRÈME code [7, 13] and the Space Environment Information System (SPENVIS) [14]. Furthermore, we use these same tool sets to develop an environmental model of the July 2000 “Bastille Day” solar event so that a comparison can be made to the October 1989 event. The October 1989 storm has been the de facto worst-case environment since the release of CRÈME96.

We focused this work on evaluating environment-specific soft error rates in a volatile and non-volatile memory technology arising from various shielding distributions: solid aluminum spheres of different thicknesses, an aluminum cube with 2.5 mm walls, an isolated spacecraft electronics box, and that electronics box embedded in an actual spacecraft. The soft error rates in these memories are dominated by direct ionization effects. We chose environments consistent with an Earth-based satellite with an highly-elliptical orbit, including trapped protons, Prediction of Solar particle Yields for Characterizing Integrated Circuits (PSYCHIC)-based solar heavy ions [4, 5], as well as GCR and two worst-case solar particle events based on the October 1989 and July 2000 storms [7]. The soft error rates are calculated with NOVICE [15, 16], using strict adjoint numerical integration techniques. These analyses will enable insightful comparisons and improve risk mitigation for NASA-relevant commercial technologies destined for flight project insertion.

Table I: Sensitive Volume Parameters

Sensitive Volume	X (nm)	Y (nm)	Z (nm)	Q_{crit} (fC)	E_{crit} (keV)
SV1 (SiO ₂)					
4 Gbit SLC NAND Flash	63	50	10	0.06	6.6
SV2 (Silicon)					
45 nm SOI SRAM	450	450	100	0.5	11

II. SENSITIVE VOLUME DESCRIPTIONS

We chose two sensitive volumes for soft error rate calculation comparison across the different environments and shielding distributions examined in this work. Their parameters are shown in Table I, where Q_{crit} is the critical charge and E_{crit} is the critical energy, implying that meeting or exceeding either one within the sensitive volume will result in a soft error. The first volume (SV1, SiO₂) is based on the oxide charge storage stack in the Samsung K9F4G08U0A 4 Gbit single-level cell NAND flash memory, which is defined based on process reverse engineering [17]. The heavy ion sensitivity of this structure was determined by accelerated ground testing, *c.f.* Fig. 3b in [18]. We calculated the critical charge based on a SiO₂ electron-hole pair creation energy of 17 eV, which translates to 106 keV/fC [19, 20]. The second volume (SV2, silicon) is derived from the 45 nm SOI static random access memory (SRAM) data presented by D. F. Heidel, *et al.* [11]. Its dimensions were derived by taking the square root of the saturated heavy ion cross section in Fig. 2 of [11] and assuming a 100 nm silicon body thickness. The critical charge is based on the electron-hole pair creation energy in silicon of 3.6 eV [21, 22]. No further technology information was used.

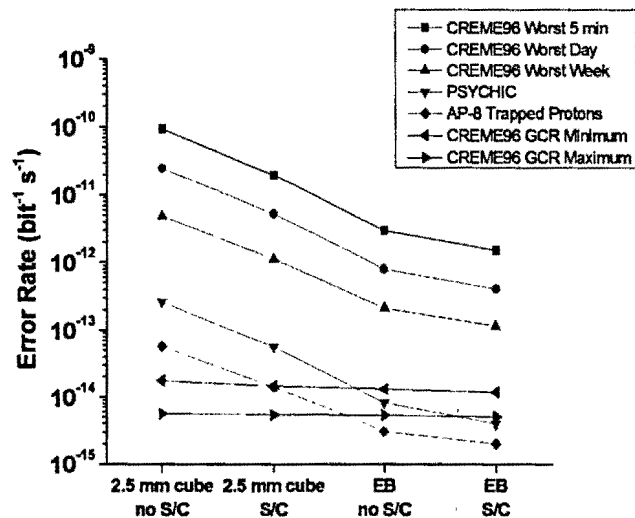


Fig. 3(a): SiO₂ SV1 soft error rates for most of the environments in this study. However, these rates consider several more realistic shielding configurations. A cube with 2.5 mm aluminum walls and an actual electronics box (EB) are simulated with and without a complete spacecraft (S/C). The cube is placed within the spacecraft such that its shielding environment is similar to the electronics box. The PSYCHIC environment was calculated at the 95% confidence level. Note that the PSYCHIC and trapped proton environments are cumulative fluences that were scaled by the inverse of the integration period to convert them to average rates.

We reached these conclusions regarding the sensitive volume dimensions and critical upset parameters based on publicly available information and several conservative assumptions. These parameter estimates are not meant to be definitive, but as a means of comparing the soft error rates of different environments and shielding configurations given a well-defined definition of upset in two distinct technologies.

III. SOFT ERROR RATE CALCULATIONS

A. NOVICE Methodology

The NOVICE soft error rate calculations produce a pulse height spectrum that is reverse-integrated to produce a curve of event counts in a sensitive volume over a given time interval versus energy deposited. The soft error rate can then be determined once the critical energy is known. An example of these soft error rate curves for SV1 is shown in Fig. 1. Based on the information in Table I, for the CRÈME96 GCR solar maximum, the 4 Gbit NAND flash would have rate of 2.4×10^{-5} errors/s behind 2.5 mm of solid spherical aluminum shielding. For GCR environments based on CRÈME96, the flux versus energy spectra for solar maximum and solar minimum represent the extreme points of the solar cycle and vary slowly.

Aside from GCR environments, we also performed rate calculations for cumulative solar maximum solar heavy ions and trapped protons. The trapped proton spectra were compiled as total fluences over 2.5 years based on the AP-8 model. The proton transport and rate calculations are unique from the other calculations in that they include elastic recoils from the surrounding material as well as the sensitive volume. The elastic recoils roughly double the pulse height counts in the larger energy bins and have the ability to extend the energy deposition distribution. We also computed the PSYCHIC solar

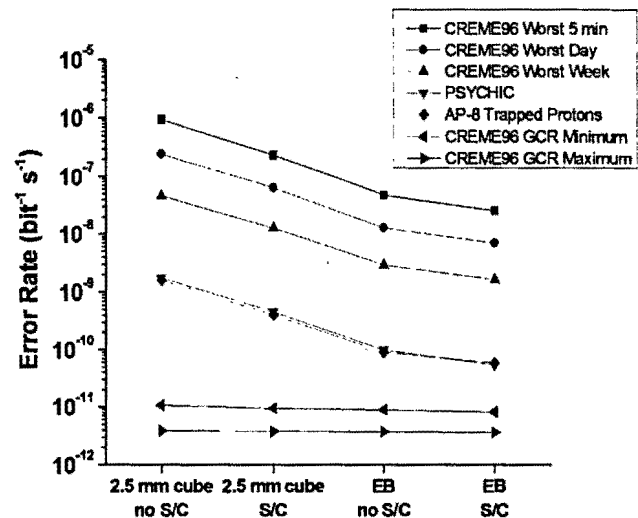


Fig. 3(b): Silicon SV2 soft error rates for most of the environments in this study. However, these rates consider several more realistic shielding configurations. A cube with 2.5 mm aluminum walls and an actual electronics box (EB) are simulated with and without a complete spacecraft (S/C). The cube is placed within the spacecraft such that its shielding environment is similar to the electronics box. The PSYCHIC environment was calculated at the 95% confidence level. Note that the PSYCHIC and trapped proton environments are cumulative fluences that were scaled by the inverse of the integration period to convert them to average rates.

heavy ion environment fluences at the 95% confidence level for one solar active year, which includes all naturally-occurring elements in the periodic table. The major components are H, He, C, N, O, Ne, Mg, Si, S, and Fe ions. The fluences for these solar heavy ions are based on data from the Interplanetary Monitoring Platform (IMP-8) Goddard Medium Energy (GME) experiment [23] and the Advanced Composition Explorer (ACE) Solar Isotope Spectrometer (SIS) [24] instruments. The trapped proton and PSYCHIC solar heavy ion environment models produce long-term averages that have been scaled by the inverse of the integration period in order to calculate an average rate per second.

We have made some fundamental assumptions about the soft error rates presented here. In the case of both sensitive volumes, we assumed a monolithic cross section, which is physically impossible. This is necessary in the absence of fundamental knowledge about the process, physical layout, and soft error mechanisms. Actually, NOVICE can do this also but it has not been rigorously verified. We neglected nuclear inelastic reactions, assuming that the observable soft error rate is driven by direct ionization of the primary particle and ionization caused by proton-based elastic reactions. In the critical energy regime of these devices, the mechanism assumption is likely valid for single-bit soft errors. Finally, the calculations presented here do not have their uncertainties evaluated, which would be a challenging undertaking.

B. Solid Aluminum Spherical Shielding

The combined plots showing the error rates for all seven environments for both sensitive volumes are shown in Figs. 2(a) and 2(b). The worst case solar particle event (SPE) environments from CRÈME96 – worst five minutes, worst day, and worst week – produce the highest rates for both SV1

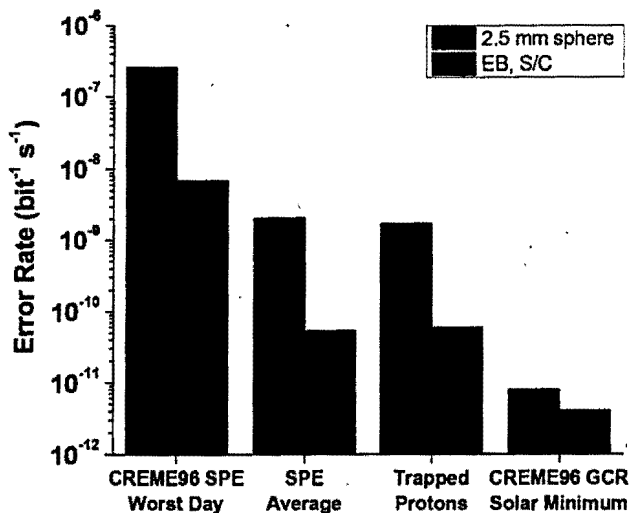


Fig. 4: Silicon SV2 comparison of environmental soft error rates for the standard 2.5 mm solid spherical aluminum shield and an electronics box (EB) within an actual spacecraft. Between the 2.5 mm solid sphere shield and the electronics box within the spacecraft, both the worst day and the solar particle event average differ by a factor of 38, trapped protons by a factor of 28, and GCR solar minimum by a factor of 2. These differences highlight the conservative nature of small-thickness spherical shielding.

and SV2. The CRÈME96 solar minimum and maximum GCR environments are not appreciably affected by increased shielding. However, shielding impacts the SPE environments, trapped protons, and PSYCHIC solar heavy ions producing large variations in soft error rates for a given shielding thickness. The soft error rate from solar heavy ion and trapped proton spectra direct ionization dominates the ambient space environment for both SV1 and SV2, though shielding can mitigate the proton rate past 10 mm of aluminum in the case of SV1. The trapped protons and solar heavy ions dominate the error rate of SV2 outside of SPE conditions up to and past 25.4 mm (1 in) of solid spherical aluminum shielding.

As a comparison to CRÈME96, several calculation points have been made for SV2. We cannot compare CRÈME96 with the NAND flash (SV1) rate calculations because the sensitive volume is SiO₂, which is not possible in the CRÈME96 framework. This is possible using the expanded features in CRÈME-MC. Using the Q_{crit} heavy ion upset prediction tool, we calculated geosynchronous solar maximum and minimum rates. The CRÈME96 rates for SV2 in solar maximum and minimum are 2.3×10^{-12} errors/(bit·s) and 6.3×10^{-12} errors/(bit·s) assuming 2.5 mm of aluminum shielding. These rates are within a factor of two of the corresponding NOVICE rates of 3.5×10^{-12} errors/(bit·s) and 9.8×10^{-12} errors/(bit·s). This level of agreement is encouraging, bearing in mind that NOVICE is actually transporting the particle flux-energy spectra through materials, including the sensitive volume, whereas CRÈME96 is combining path lengths with a linear energy transfer spectrum in the sensitive volume.

C. Spacecraft Shielding

Radiation engineers and scientists use solid spherical shielding in the absence of more detailed mechanical models or because use of such models is outside the scope of work. Standard practice assumes 2.5 mm – roughly 100 mil – of solid spherical aluminum to provide uniform 4π sr coverage.

However, detailed analysis of actual spacecraft electronics boxes and superstructure generally shows that 2.5 mm of shielding is an underestimation. In truth, many electronics boxes have walls that are thicker than 2.5 mm, and that does not consider the additional mass of the surrounding spacecraft. Furthermore, rectangular parallelepipeds do not provide uniform shielding over 4π sr like spherical shielding. Sensitive volumes close to edges and corners will receive much more shielding because incident particles must travel longer distances when incident at grazing angles.

Table II: Electronics Box NOVICE Ray Path Statistics

Box Type	Minimum (mm)	Maximum (mm)	Average (mm)
Cube, no S/C	2.54	4.34	2.97
Cube, in S/C	2.62	1810	4.75
Electronics box, no S/C	4.45	108	15.9
Electronics box, in S/C	4.45	1620	23.4

The spacecraft used in this study has a dry mass of approximately 800 kg, is octagonal in shape, has decks enclosing the top and bottom faces, and is wrapped in its solar panels. The electronics box used is the central instrument data processor box, which is part of the command and data handling infrastructure. This box is made of aluminum and is located inside the spacecraft, approximately half way between the top and bottom decks. Table II shows the ray path statistics for a cube with 2.5 mm walls and the central instrument data processor electronics box.

Figs. 3(a) and 3(b) show soft error rates for SV1 and SV2 in various realistic configurations that do not rely on spherical shielding. As expected, the solar particle event and trapped proton environments are more sensitive to the amount of shielding than GCR. These shielding configurations also demonstrate the same behavior as the solid spherical shielding in Figs. 2(a) and 2(b) in that the large amount of shielding around SV1 eventually blocks out the contributions from trapped protons and solar particles, leaving GCR to dominate the soft error rate. SV2 is always dominated by trapped protons and solar particles. It is important to note that the complete electronics box provides the largest amount of independent shielding – more than the generic cube within the spacecraft and more than the spacecraft itself. The critical point is that the average ray path thickness of the electronics box inside the spacecraft is larger by a factor of five relative to the average ray path thickness of the 2.5 mm-walled cube inside the spacecraft.

While isolated, perhaps these comparisons between different shielding environments do not seem significant. However, on closer examination, the difference is more than a factor of 25 between the complete electronics box inside the spacecraft and 2.5 mm of solid spherical shielding for all but the GCR solar minimum environment. This is shown in Fig. 4.

D. Examination of the July 2000 Event

Throughout this investigation, we have only considered the October 1989 solar particle event in terms of worst case environments. It is known to radiation effects engineers as the worst week, worst day, and worst five minutes selections in

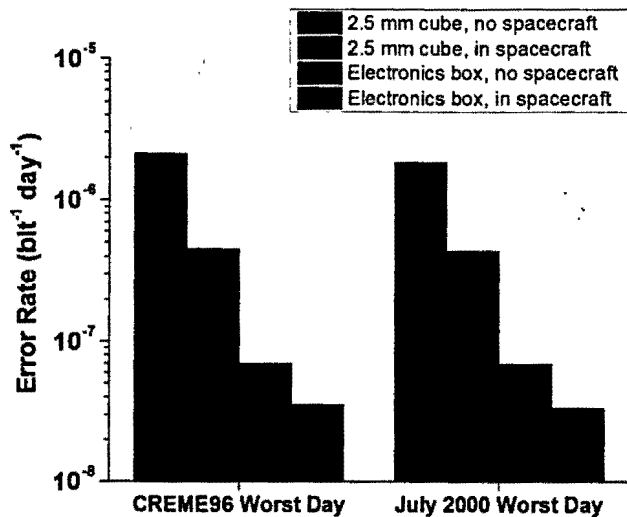


Fig. 5(a): SiO₂ SV1 soft error rate comparison for the worst day during the past two solar maximum periods – the October 1989 event and the July 2000 event. The cube, electronics box, and spacecraft are the same as those discussed earlier.

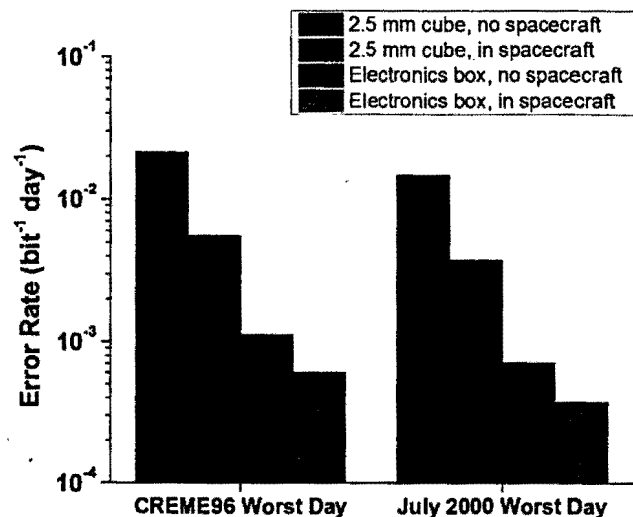


Fig. 5(b): Silicon SV2 soft error rate comparison for the worst day during the past two solar maximum periods – the October 1989 event and the July 2000 event. The cube, electronics box, and spacecraft are the same as those discussed earlier.

CRÈME96 and CRÈME-MC tool suites. The solar maximum period following the one that produced the October 1989 storm produced another very large solar particle event in July 2000. The particle fluxes for the July 2000 event remained above background for more than one month. However, the highest fluxes by far, particularly for heavy ions, occurred over a period of a few days shortly after the event onset. Previous measurements of LET spectra by C.S. Dyer *et al.* have shown that this event and two others during solar cycle 23 approximately equaled the “worst day” model in CRÈME96 [25]. Thus, further investigation is warranted. We have therefore analyzed the IMP-8 GME and ACE SIS data for the worst two day period of the July 2000 event to obtain energy spectra of the 10 most abundant elements as outlined in [5]. Other satellite data and an abundance model were used to determine the relatively small contributions of the remaining naturally occurring elements in the periodic table, again as in [5]. Since the worst two-day period was used, the number of calculated upsets were divided by 2 before comparison to the upsets produced by the worst day portion of the October 1989 event in the CRÈME models. A period of 2 days was chosen because the fluxes of different ions peak at different times during this period and it was not clear that initially limiting our analysis to 24 hours would be “worst case” for both memories that we consider.

Figs. 5(a) and 5(b) show SV1 and SV2 soft error rates for the October 1989 and July 2000 worst days for the cube with 2.5 mm walls and the electronics box, both with and without the spacecraft. SV1 produces similar results for both events and is insensitive to any differences in event composition. SV2 yields higher soft error rates for the October 1989 worst day environment, though the increase over July 2000 is only a factor of two. We conclude that the two events are similar given our stated geometries and upset sensitivities.

IV. DISCUSSION

The soft error rate calculations presented in Section III, while for simple shielding geometries, reveal interesting trends and highlight issues necessary for spacecraft mission assurance. The two most critical aspects of the simulation results presented in Figs. 2 and 3 are the contributions from solar heavy ions and trapped protons, recalling that NOVICE only computed direct ionization of the primary particle and any elastic recoils produced during the trapped proton computations. We showed that the October 1989 SPE is still sufficient for worst case analysis, but the margin available for a given application could result in either over- or underestimation of the soft error risk, yielding higher costs for unintentional over-engineering, redesign, or anomaly resolution.

In the past, with larger, less sensitive technologies, the effects of protons were limited to TID, displacement damage effects, and single-event effects related to indirect ionization. However, as commercial vendors scale CMOS and SOI technologies, direct ionization proton events have become reality [10-12]. A large portion of the weight in the solar particle and trapped proton rates considered here is due to direct ionization, which, given their abundance, drives up the soft error rate. We did not intentionally focus this work on low-energy proton rate calculations, but the effect is substantial for certain geometries. Note that for SV1, the error rates for trapped protons and the long-term solar particle environment are brought down to a comparable level with GCR solar maximum through the use of the heavily shielded electronics box. On the other hand, for SV2 they remain well above the GCR rates. While the critical energies for SV1 and SV2 are within a factor of two, the electron-hole pair creation energy is different and the size of SV1 is much smaller. In fact, the volume of SV2 is over six hundred times larger than the volume of SV1, making it easier to deposit the critical energy.

We note the substantial contribution from solar heavy ions, which equals or exceeds the GCR contribution during the solar maximum period. Traditionally, average solar heavy ion fluences are not modeled when doing basic rate calculations, but this work suggests that they are important with sensitive technologies. The PSYCHIC solar heavy ion model also includes proton fluences as calculated in the Emission of Solar Protons (ESP) model [3-5], and is therefore a confidence level based approach. In the future, when evaluating soft error rates for sensitive technologies, it may be necessary to incorporate solar heavy ions on a regular basis.

V. CONCLUSIONS

We have demonstrated that the use of simplified assumptions of solid sphere shielding generally overestimate soft error rates due to direct ionization. This can be especially important in modern commercial devices with low upset thresholds and scaled geometries. Using solid sphere shielding assumptions may lead to overdesign and increased mission cost.

For the sensitive volume examples considered here, the soft error rates were overestimated by about 2x for GCR during solar minimum, 28x for the long-term solar particle and trapped proton environments, and 38x for the CRÈME96 worst day. This is analogous to TID and displacement damage dose requirement trends with shielding analysis. For the two memories considered, the trapped proton environment, not the widely quoted GCR environment, always contributed substantially and often dominated the soft error rates under ambient conditions. To better understand this effect, more shielding configurations and orbits should be analyzed. In addition to trapped protons, the solar particle environment can also cause more soft errors than GCR over the long-term during solar maximum periods.

Due to the increasing importance of shielding analysis for SEE, tools like NOVICE and Geant4-based applications (CRÈME-MC and SPENVIS/MULASSIS) are becoming necessities. These tools need to be validated with space data.

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REFERENCES

- [1] *STP Magnetospheric MultiScale Mission*. Available: <http://stp.gsfc.nasa.gov/missions/mms/mms.htm>; <http://mms.space.swri.edu/>
- [2] J. L. Burch and J. F. Drake, "Reconnecting magnetic fields," *American Scientist*, vol. 97, no. 5, pp. 392-399, Sep-Oct 2009.
- [3] M. A. Xapsos, G. P. Summers, J. L. Barth, E. G. Stassinopoulos, and E. A. Burke, "Probability model for cumulative solar proton event fluences," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 3, pp. 486-490, Jun. 2000.
- [4] M. A. Xapsos, C. Stauffer, G. B. Gee, J. L. Barth, E. G. Stassinopoulos, and R. E. McGuire, "Model for solar proton risk assessment," *IEEE Trans. Nucl. Sci.*, vol. 51, no. 6, pp. 3394-3398, Dec. 2004.
- [5] M. A. Xapsos, C. Stauffer, T. Jordan, J. L. Barth, and R. A. Mewaldt, "Model for cumulative solar heavy ion energy and linear energy transfer spectra," *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, pp. 1985-1989, Dec. 2007.
- [6] J. Feynman and S. B. Gabriel, "High-energy charged particles in space at one astronomical unit," *IEEE Trans. Nucl. Sci.*, vol. 43, no. 2, pp. 344-352, Apr. 1996.
- [7] A. J. Tylka, J. H. Adams Jr, P. R. Boberg, B. Brownstein, W. F. Dietrich, E. O. Flueckiger, E. L. Petersen, M. A. Shea, D. F. Smart, and E. C. Smith, "CRÈME96: a revision of the Cosmic Ray Effects on Micro-Electronics Code," *IEEE Trans. Nucl. Sci.*, vol. 44, no. 6, pp. 2150-2160, Dec. 1997.
- [8] R. A. Weller, R. A. Reed, K. M. Warren, M. H. Mendenhall, B. D. Sierawski, R. D. Schrimpf, and L. W. Massengill, "General framework for single event effects rate prediction in microelectronics," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 6, pp. 3098-3108, Dec. 2009.
- [9] *CRÈME96: Cosmic Ray Effects on Microelectronics*. Available: <https://creme96.nrl.navy.mil/>
- [10] D. F. Heidel, P. W. Marshall, K. A. LaBel, J. R. Schwank, K. P. Rodbell, M. C. Hakey, M. D. Berg, P. E. Dodd, M. R. Friendlich, A. D. Phan, C. M. Seidleck, M. R. Shaneyfelt, and M. A. Xapsos, "Low energy proton single-event upset test results on 65 nm SOI SRAM," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, pp. 3394-3400, Dec. 2008.
- [11] D. F. Heidel, P. W. Marshall, J. A. Pellish, K. P. Rodbell, K. A. LaBel, J. R. Schwank, S. E. Rauch, M. C. Hakey, M. D. Berg, C. M. Castaneda, P. E. Dodd, M. R. Friendlich, A. D. Phan, C. M. Seidleck, M. R. Shaneyfelt, and M. A. Xapsos, "Single-event upsets and multiple-bit upsets on a 45 nm SOI SRAM," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 6, pp. 3499-3504, Dec. 2009.
- [12] B. D. Sierawski, J. A. Pellish, R. A. Reed, R. D. Schrimpf, K. M. Warren, R. A. Weller, M. H. Mendenhall, J. D. Black, A. D. Tipton, M. A. Xapsos, R. C. Baumann, D. Xiaowei, M. J. Campola, M. R. Friendlich, H. S. Kim, A. M. Phan, and C. M. Seidleck, "Impact of low-energy proton induced upsets on test methods and rate predictions," *IEEE Trans. Nucl. Sci.*, vol. 56, no. 6, pp. 3085-3092, Dec. 2009.
- [13] *CRÈME-MC: CRÈME Monte Carlo*. Available: <https://creme-mc.isde.vanderbilt.edu/>
- [14] *SPENVIS: The Space Environment Information System*. Available: <http://www.spenvis.oma.be/>
- [15] T. M. Jordan, "An adjoint charged particle transport method," *IEEE Trans. Nucl. Sci.*, vol. 23, no. 6, pp. 1857-1861, Dec. 1976.
- [16] T. M. Jordan, "The accuracy of NOVICE electron shielding calculations," in *1st European Conf. on*

- Radiation and Its Effects on Components and Systems*, La Grande-Motte, France, 1991, pp. 320-324.
- [17] D. James, "Nano-scale flash in the mid-decade," in *Advanced Semiconductor Manufacturing Conf.*, Stresa, Italy, 2007, pp. 371-376.
- [18] T. R. Oldham, M. R. Friendlich, A. B. Sanders, C. M. Seidleck, H. S. Kim, M. D. Berg, and K. A. LaBel, "TID and SEE response of advanced Samsung and Micron 4G NAND flash memories for the NASA MMS mission," in *IEEE Radiation Effects Data Workshop*, Quebec City, Quebec Canada, 2009, pp. 114-122.
- [19] J. G. A. Ausman and F. B. McLean, "Electron - hole pair creation energy in SiO₂," *Appl. Phys. Lett.*, vol. 26, no. 4, pp. 173-175, Feb. 1975.
- [20] J. M. Benedetto and H. E. Boesch, "The relationship between ⁶⁰Co and 10 keV x-ray damage in MOS devices," *IEEE Trans. Nucl. Sci.*, vol. 33, no. 6, pp. 1317-1323, Dec. 1986.
- [21] C. A. Klein, "Bandgap dependence and related features of radiation ionization energies in semiconductors," *J. Appl. Phys.*, vol. 39, no. 4, pp. 2029-2038, Mar. 1968.
- [22] R. C. Alig and S. Bloom, "Secondary-electron-escape probabilities," *J. Appl. Phys.*, vol. 49, no. 6, pp. 3476-3480, Jun. 1978.
- [23] *Interplanetary Monitoring Platform (IMP-8)*. Available: <http://spdf.gsfc.nasa.gov/imp8/project.html>
- [24] *Advanced Composition Explorer (ACE)*. Available: <http://www.srl.caltech.edu/ACE/>
- [25] C. S. Dyer, K. Hunter, S. Clucas, D. Rodgers, A. Campbell, and S. Buchner, "Observation of solar particle events from CREDO and MPTB during the current solar maximum," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 6, pp. 2771-2775 Dec. 2002.